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**ON DYNAMIC STABILITY OF NUCLEAR POWER  
PLANTS**

P.A.Gavrilov, L.N.Podlazov.

Nuclear power plants intended to operate in remote, difficult-to-reach areas of the country have to possess not only high safety but also definite dynamic characteristics.

A low power plant, operating out of the power system and supplying a small number of consumers, can be exposed to considerable external load changes. Practically it must be stable and withstand the full external load removing and increase. It should be taken into account that from the economic point of view, pump and control system drives and another plant electric equipment is advisable to be power supplied from the same turbogenerator as well as external consumers. In addition, the plant control system must be the simplest, not requiring highly skilled specialists to operate it.

Therefore it seems to be necessary to use to the maximum self-regulating properties of power systems.

The object of the present paper was to study peculiarities and the character of transients of nuclear power plants, at which a steam generator had a boiling water free level. As studies have shown, the dynamic properties of nuclear plants of this type meet the requirements of "small-sized nuclear power plants".

Steam generators with boiling water free level usually have relatively large secondary circuit water capacity. Transients in power plants with such a steam generator, dependent on changes of secondary circuit parameters (steam extraction, feed water

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flow rate and its temperature) run with great time delay, slowly as compared to the reactor transients. Because of this the latter may be considered to be quasi-static and studying the system dynamic stability as a whole the reactor should be considered only in a quasi-static asymptotic approximation. It means that the influence of terms of high orders in the reactor transfer function is neglected. The whole system may turn out to be aperiodically stable even at oscillatory stability of the reactor. As far as high oscillation frequencies, which can be caused in the reactor by different reasons, are filtered at a steam generator and in other primary circuit units great enough and does not pass to reactor input, the system proves to be "unclosed" over high frequencies. The closed system stability problem can be reduced to the dynamic stability study of the reactor at these frequencies and of the closed system, in which the reactor is represented in a quasi-stationary approximation.

While writing down the system of the dynamics equations we have taken a series of simplifying assumption, validity of which is evident enough. The main of them are as follows:

- a) Primary circuit coolant flow rate is constant.
- b) Steam extraction to the turbine is directly proportional to the load.
- c) Feed water supply depends on the change of steam flow rate to the turbine and is carried out through an aperiodic network.
- d) One group of delayed neutrons was considered in the equations of kinetics.
- e) Feed water subcooling was taken into account in the total steam generator heat balance.
- f) The final velocity of upward steam flow in the boiling zone was neglected, that is, boiling water level change because of the void steam content change was ignored.
- g) Saturation temperature - pressure dependence is linear.
- h) Heat-transfer coefficients are constant. For the reactor it is the consequence of the assumption of the coolant flow rate permanency. It is true for a steam generator if the heat-transfer coefficient is slightly dependent on heat flux.

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- i) Reactivity changes are small and the equations of kinetics may be linearized.
- j) Transport delays in pipings were approximate by an aperiodic network.

The solution of the system of the reactor dynamics equations can be expressed with these rather general approximations as the transfer function  $\alpha(s)$  which describes coolant temperature changes at the reactor outlet with temperature fluctuations at the reactor inlet. Let this function be conventionally "the reactor transfer function" though it usually denotes the function which is characteristic of power changes versus reactivity changes:

$$\alpha(s) = - \frac{\tilde{v}_{\text{outlet}}}{\tilde{v}_{\text{inlet}}} = - \frac{F_1(s)}{F_0(s)} \quad (1)$$

where

$$\begin{aligned} F_0(s) &= s(s + T_M^P)(s + T_H^P + 0.5T_I^P) - 0.5sT_M^PT_I^P - \alpha_e^* A_0 T_I(s + T_0) \\ F_1(s) &= s(s + T_M^P)(T_H^P - 0.5T_I^P) + 0.5sT_M^PT_I^P + \alpha_i^* A_0 T_I(s + T_0) \end{aligned} \quad (2)$$

The functions  $\alpha_e^*(s)$  and  $\alpha_i^*(s)$  are correspondingly equal.

$$\begin{aligned} \alpha_e^*(s) &= \alpha_e + \beta_0 s \\ \alpha_e &= 0.5\alpha_T \bar{\theta}_0 \left\{ 1 + \left( 1 + 2 \frac{T_H^P}{T_I^P} \right) \frac{\beta_T}{\alpha_T} \right\} \\ \beta_0 &= \frac{\bar{\theta}_0}{T_I^P} \\ \alpha_i^*(s) &= \alpha_i = 0.5\alpha_T \bar{\theta}_0 \left\{ 1 + \left( 1 - 2 \frac{T_H^P}{T_I^P} \right) \frac{\beta_T}{\alpha_T} \right\} \end{aligned} \quad (3)$$

The reactivity changes can be represented as a function of reactor inlet and outlet coolant temperature:

$$\tilde{\rho}_T = \alpha_i^*(s) \tilde{v}_{\text{inlet}} + \alpha_e^*(s) \tilde{v}_{\text{outlet}} \quad (4)$$

It is seen from equations (1) and (2) that the reactor as a dynamic system has a characteristic equation of the third order. However, in most cases the function  $\alpha(s)$  can be simplified by neglecting the terms  $s^3$  and  $s^2$  as the heat-transfer coefficient and the fuel element heat conductivity and hence the reactor dynamic constants usually are proved to be great enough.

Besides that, high frequency components in the function of inlet coolant temperature changes in a closed reactor system are negligible.

If the steam generator boiling water level is assumed to be held approximately constant at all transients due to controlled feed water supply and is assumed to be left above the coil levels, then it is easy to get the relation between  $\tilde{v}_{inlet}$  and  $\tilde{v}_{outlet}$  solving steam generator heat transfer equations

$$\tilde{v}_{inlet} = f(s) \left\{ A_1 \tilde{v}_{outlet} + (s + T_1) \frac{A_2}{T_1} \tilde{p} \right\} \quad (5)$$

where

$$f(s) = \frac{T^{sg} \cdot T_1 \cdot T_2}{(s + T^{sg})(s + T_1)(s + T_2)} \quad (6)$$

The function  $f(s)$  can be considered the transient function of series-connected aperiodic networks. The dynamic coefficients  $T^{sg}, T_1, T_2$  are always positive. Therefore, the steam generator, as a dynamic system, is absolutely stable as to the inlet temperature disturbances and to the secondary circuit pressure.

Introducing effective delay time  $\tau^{eff} = \tau_1 + \tau_2 + \tau^{sg}$ , the function  $f(s)$  can be expressed as an aperiodic network

$$f(s) = \frac{\tau^{eff}}{s + \tau^{eff}} \quad (7)$$

where

$$\tau^{eff} = \frac{\tau_0}{\tau^{eff}} \quad (8)$$

In case of a reactor with a control system, it is necessary to introduce the equations of an automatic power regulator into the system of equations of the reactor dynamics. The former can be written down considering possible corrections for the process parameters (pressure, temperature and etc.) in the form

$$\begin{aligned} s\tilde{p}_d &= x_1(\tilde{n} - \tilde{n}_3) \\ s\tilde{n}_3 &= x_2\tilde{n}_3 + x_3\tilde{p} + 2(x_4 + x_5 s)\tilde{v} \end{aligned} \quad (9)$$

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In this case the system reactivity changes at pressure disturbances (external load) and at introducing the correction for the steam pressure power demand can "be decomposed" into two components: a "temperature" component  $\tilde{\rho}_T$  due to coolant temperature changes and a "pressure" component  $\tilde{\rho}_p$ . Also, the third component  $\tilde{\rho}_j$ , characterizing a random uncontrolled reactivity fluctuations, can be introduced. Thus

$$\tilde{\rho}(s) = \tilde{\rho}_T^{\text{eff}}(s) + \tilde{\rho}_p(s) + \tilde{\rho}_j(s) \quad (10)$$

where

$$\begin{aligned} \tilde{\rho}_T^{\text{eff}}(s) &= \alpha_i^{\text{eff}}(s) \tilde{v}_{\text{inlet}} + \alpha_e^{\text{eff}}(s) \tilde{v}_{\text{outlet}} \\ \tilde{\rho}_p(s) &= x_p^{\text{eff}}(s) \tilde{p}. \end{aligned} \quad (11)$$

Then, effective "temperature" coefficients of reactivity ( $\alpha_i^*(s)$ ;  $\alpha_e^*(s)$ ) and an effective "pressure" coefficient of reactivity can be expressed in terms of reactor process parameters and of power regulator parameters as follows:

$$\begin{aligned} \alpha_i^{\text{eff}}(s) &= \frac{\alpha_i^*(s-x_2)s - x_1(x_4 + x_5 s)}{(s-x_2)(s^2 - x_1 s - x_1 T_0)} s \\ \alpha_e^{\text{eff}}(s) &= \frac{\alpha_e^*(s)(s-x_2)s - x_1(x_4 + x_5 s)}{(s-x_2)(s^2 - x_1 s - x_1 T_0)} s \\ x_p^{\text{eff}}(s) &= \frac{x_1 x_2}{(s-x_2)(s^2 - x_1 s - x_1 T_0)} s \end{aligned} \quad (12)$$

Hence, due to linearity of the system of the dynamics equations, the other process parameter changes (e.g.  $\tilde{v}_{\text{outlet}}$ ,  $\tilde{n}$ ) also can "be decomposed" formally into "temperature", "pressure" and "reactivity jump" components.

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$$\tilde{v}_{\text{outlet}} = \frac{F_i(s)}{F_0(s)} \tilde{v}_{\text{inlet}} + \frac{F_p(s)}{F_0(s)} \tilde{p} + \frac{F_j(s)}{F_0(s)} \tilde{p}_j \quad (13)$$

where  $F_0(s)$  and  $F_i(s)$  coincide in form with the functions (2) which incorporate the relations (12) instead of  $\alpha_e^*$  and  $\alpha_i^*$ , but  $F_p(s)$  and  $F_j(s)$  are equal, respectively:

$$\begin{aligned} F_p(s) &= \frac{\alpha_p^{\text{eff}}(s)}{s} (s + T_0) A_0 T_1^P = - \frac{\alpha_1 \alpha_2 A_0 T_1^P (s + T_0)}{(s - \alpha_2)(s^2 - \alpha_1 s - \alpha_1 T_0)} \\ F_j(s) &= \frac{\alpha_j^{\text{eff}}(s)}{s} (s + T_0) A_0 T_1^P = \frac{A_0 T_1^P s (s + T_0)}{(s - \alpha_2)(s^2 - \alpha_1 s - \alpha_1 T_0)} \end{aligned} \quad (14)$$

It should be noted that to provide the best quality of the transients the automatic power control systems are designed so that time constants of reactor power setting changes and corrections are turned out to be much greater than a time constant of a neutron power regulator, i.e.

$$|\alpha_1| \gg |\alpha_2, \alpha_3, \alpha_4, \alpha_5|$$

It means, that the rate of a neutron power change is much greater than that of a power setting change, power follows changes of a power demand setting, i.e.  $n \approx n_s$  at any time instant. Furthermore, the automatic control rod (AP) insertion rate at autonomous regulator adjustment is usually selected so that a control rod (AP) could overcome the "resistance" of a negative temperature reactivity effect and assure a good quality of reactor power transients. It means that the first addend in the numerator of the expressions for  $\alpha_i^{\text{eff}}$  and  $\alpha_e^{\text{eff}}$  in (12) must be much less at all frequencies characteristic of the reactor. Hence, neglecting the influence of the temperature effect, while the automatic control rod (AP) is in operation and assuming that AP is adjusted so well that it does not cause systematic disturbances of low frequencies in a closed reactor dynamic system, the following equations can be written down instead of equations (12):

$$\begin{aligned}\alpha_i^{\text{eff}}(s) &= \alpha_e^{\text{eff}}(s) \approx \frac{\alpha_4 + \alpha_5 s}{(s - \alpha_2)(s + T_0)} s \\ \alpha_p^{\text{eff}}(s) &\approx \frac{\alpha_3}{(s - \alpha_2)(s + T_0)} s \\ \alpha_j^{\text{eff}}(s) &\approx \frac{s}{\alpha_1(s + T_0)}\end{aligned}\quad (15)$$

With power automatic control system and with due regard for equations (15), the functions  $F_0(s)$  and  $F_1(s)$  take the form:

$$F_0(s) = (s - \alpha_2) \left[ (s + T_H^p)(s + T_H^p + 0.5T_1^p) - 0.5T_H^p T_1^p \right] - A_0 T_1^p (\alpha_4 + \alpha_5 s) \quad (16)$$

$$F_1(s) = (s - \alpha_2) \left[ (s + T_H^p)(T_H^p - 0.5T_1^p) + 0.5T_H^p T_1^p \right] + A_0 T_1^p (\alpha_4 + \alpha_5 s) \quad (17)$$

The multiplier  $(s - \alpha_2)$  in the dominator is omitted as being unessential.

As an example, some results of the APEYC plant dynamic property studies are to be given. As the time characteristics of processes, run at the APEYC plant, are calculated to be a few tens of seconds, then the reactor thermal processes can be considered in a quasi-static approximation. It allows to write down the functions  $F_0(s)$  and  $F_1(s)$  from the equations (2) in the form

$$\begin{aligned}F_0(s) &\approx K_e (s + T_e) \\ F_1(s) &\approx K_i (s + T_i)\end{aligned}\quad (18)$$

Expressions for  $K_e$ ,  $K_i$ ,  $T_1$ ,  $T_e$  are given in Table III.

In this case the system characteristic equation will be written down as

$$s^3 + \chi s^2 + \zeta s + B_0 = 0 \quad (19)$$

where

$$X = \frac{1}{1-f} \left\{ \left[ D \left( 2 - \frac{T^{\text{eff}}(T_1 + T_2)}{T_1 T_2} (1 - A_1) \right) + T_e \left( 1 - \frac{DT^{\text{eff}}}{T_1 T_2} (1 - A_1) \right) + \right. \right. \\ \left. \left. + T^{\text{eff}} \left( 1 - A_1 \frac{K_i}{K_e} \right) \right] + \left[ x'_3 \frac{D}{T_1} \frac{A_0 T_1^p}{K_e} \right] \right\} \quad (20)$$

$$\zeta = \frac{1}{1-f} \left\{ \left[ T_e T^{\text{eff}} \left( 1 - A_1 \frac{K_i T_i}{K_e T_e} \right) + DT^{\text{eff}} (1 + A_1) \left( 1 - \frac{K_i}{K_e} \right) + \right. \right. \\ \left. \left. + DT_e \left( 2 - \frac{T^{\text{eff}}(T_1 + T_2)}{T_1 T_2} (1 + A_1) \right) \right] + \right. \\ \left. + \left[ -x'_3 D \frac{A_0 T_1^p}{K_e} \left( 1 + \frac{T^{\text{eff}}}{T_2} - \frac{T^{\text{eff}}}{T_1} \right) \right] \right\} \quad (21)$$

$$B_0 = DT^{\text{eff}} T_e (1 + A_1) \left( 1 - \frac{K_i T_i}{K_e T_e} \right) - x'_3 DT^{\text{eff}} \frac{A_0 T_1^p}{K_e} \quad (22)$$

Similarity factor  $\tau_0$  is determined, if  $B_0$  in the equation (22) is equal to a unit.

Coefficients of the equation (19) and  $\tau_0$  being applicable to the APEVC plant, are equal

$$\begin{aligned} \tau_0 &\approx 81 \\ \zeta &\approx 3.2 \\ X &\approx 2.6. \end{aligned}$$

To study the roots of the characteristic equation (19), one can use diagrams (Fig.1), represented in the paper by Vyshnegradsky (2).

Notations, used in Fig.1, are as follows:

- $\tau_s, \tau_{si}$  - doubling period of a transient exponential component
- $\beta$  - dimensionless oscillation frequency of a transient periodic component
- $\rho$  - damping characteristic of oscillation amplitude of a transient periodic component.

Region I - aperiodic stability region

## Region II - oscillatory stability region

The position of a determining point with coordinates  $(X, \zeta)$ , corresponding to a system dynamic parameters on Vyshnegradsky diagrams, allows to judge of the transient character in the system.

It is seen from Fig.1, that the APEYC plant as a dynamic system is a stable low oscillatory system; a doubling period of a transient aperiodic component is

$$t_o = \frac{\tau_o \tau_s}{0.693} \approx 140 \text{ sec};$$

an oscillatory period is

$$T = \frac{2\pi \cdot \tau_o}{\beta} \approx 500 \text{ sec};$$

the degree of an aperiodic component damping is:

$$d = \frac{\beta \lambda_u \rho}{2\pi} \approx |-3|$$

Time power and steam pressure change curves at a jump change in external load of 45% from nominal received on an analogue computer for a full initial non-linear system and without reactor simplifying assumptions are shown in Fig.2. It is evident from the given evaluations and curves that transients at the APEYC plant are almost aperiodic, so that practically an oscillatory component can be neglected. It means that the transient can be practically approximated to a transfer function, equivalent to an aperiodic network of a type  $(s + \frac{0.693}{\tau_s})^{-1}$ , where  $\tau_s$  depends on the plant parameters through the coefficients  $X$  and  $\zeta$ .

The comparison of transients investigation results on the analogue computer by using the complete non-linear system of equations with those received from Vyshnegradsky diagrams (1,2), while using the third order characteristic equation (19), has shown that this characteristic equation gives quite exact results and can be used for studies in the influence of different dynamic factors on the reactor stability.

Let us note that the dynamic coefficients  $D$ ,  $T^{\text{eff}}$ ,  $A$  and  $K_T/K_e$ ,  $T_i$ ,  $T_e$ , included in the characteristic equation coefficients (19), depend on:

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D - thermal-physical and design parameters of the secondary circuit;

$\Lambda, T^{\text{eff}}$  - heat transfer in the steam generator and transport heat transfer along the pipings and steam generators of the primary circuit;

$\frac{K_1}{K_0}, T_1, T_0$  - the reactor physical, thermal and design parameters.

It allows to investigate independently the influence of parameters of the reactor, steam generator and primary and secondary circuit coolant units on the position of the determining point at Vyshnegradsky diagram and correspondingly on the change in the plant dynamic characteristic by varying only some generalized parameters.

The influence of  $T^{\text{eff}}$ ,  $\alpha_T$  and D on the space position of the determining point of the parameters  $\chi$  and  $\zeta$  is shown in Fig.3.

Let us note, that the increase in  $T^{\text{eff}}$  is physically equivalent to the time decrease in the transport delay in primary circuit piping and steam generator and to improvement of the heat transfer conditions in the circuit.

It is seen from the curves in Fig.3, that the determining point shifts to an aperiodic stability region when increasing  $T^{\text{eff}}$  to about 0.15 (i.e. 10 times as high), other conditions being equal.

The influence of the reactor dynamic parameters on the stability of a closed power system, being self-regulated, can be evaluated, if the coefficients  $K_1/K_0, T_1, T_0$  are expressed in the reactivity temperature coefficient ( $\alpha_T$ ).

In Fig.3 the curve of changes in the determining point position in a phase space versus the value of  $\alpha_T$  with constant  $\beta_T$  and complex  $\alpha_p T_0$  being determined with reactor characteristics is shown. It is seen from the curve that the determining point shifts into the aperiodic stability region, the negative reactivity coefficient increasing.

If  $|\alpha_T|$  decreases the curve limits the aperiodic stability region, being in the oscillatory stability region. With positive reactivity coefficient  $\alpha_T > 0$  close to the fuel negative reactivity coefficient  $|\beta_T|$  the dynamic closed system

is transferred by jump into the region of absolute instability. In the same Fig. 3 the determining point position is shown versus the secondary circuit parameters, expressed in the generalized dynamic coefficient D.

Studying the curves in Fig.3, one can conclude that the change in the APBYC type nuclear power plant parameters in a wide range does not shift it into the dynamic instability region, if the reactivity temperature coefficients remains negative.

As with these changes the determining point is moving near the aperiodic stability region, rounding it, dimensionless time transient character is of a small change (i.e. the transients have almost an aperiodic character with the great damping decrement).

With a large negative temperature coefficient and primary circuit small transport delays the reactor system of APBYC type tends to transfer into the region of an aperiodic stability.

On the basis of equations (20-22), table III and also of curves, in Fig.3, one can evaluate the influence of some control system parameters.

Thus, for example, coefficients  $\mathcal{X}_4, \mathcal{X}_5$  are similar to the reactivity "temperature" coefficients  $\alpha_i$  and  $\alpha_e$ . Coefficients  $\mathcal{X}_4, \mathcal{X}_5$  increasing, the determining point will tends to an aperiodic stability boundary as in case of  $|\alpha_T|$  increase. The coefficient  $\mathcal{X}_2$  is similar to  $\beta_0$ .

While choosing the optimum dynamic parameters both the character of a transient and the magnitude of asymptotic deviation of the plant process parameters are of importance, in particular, the minimum deviation of steam pressure from a nominal value at any load disturbances.

The calculations have shown that the less the asymptotic pressure value ( $S \rightarrow 0$ ), the plant operating under self-regulation conditions, the better the steam generator heat transfer conditions (KF) and this value depends on the initial pressure value:

$$\Delta P_{\infty} = - \frac{(A_3 + A_5) \left(1 + \frac{\alpha_i}{\alpha_e} A_1\right)}{D (1 + A_1) \left(1 + \frac{\alpha_i}{\alpha_e}\right)} \Delta W_T \approx - \frac{\Gamma + \Delta i'}{\left(\frac{\partial T_s}{\partial p}\right)_{p_0} KF} \Delta W_T \quad (23)$$

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For the APEYC plant under self-regulation conditions of operation the relative pressure change is equal to about 25% of (i.e. about 6 atm.) while tripping out the full external load, which amounts to about 60% of full power.

While taking into account transient character being close to aperiodic and pressure deviation from the nominal, it is possible to say, that the APEYC plant can be in stable operation under self-regulation conditions (without AP), at least, under conditions when external load changes do not exceed 30% of the full power.

Pressure deviation from the nominal value ( $\Delta P_\infty$ ) for the given type of a steam generator can be reduced by making corrections for pressure in automatic power regulator reading and by selecting corresponding parameters  $\alpha_2$  and  $\alpha_3, \alpha_4$ . Then  $\Delta P_\infty$  will be equal

$$\Delta P_\infty = - \frac{(A_3 + A_5) [(1 - A_1) - (1 + A_1) \alpha_p \frac{\alpha_4}{\alpha_2}]}{D(1 + A_1) \alpha_p (\frac{\alpha_4}{\alpha_2} + \frac{1}{\psi} \frac{\alpha_3}{\alpha_2})} \Delta W_T.$$

In case of the APEYC plant pressure correction allows to reduce relative pressure change at tripping out 60% of full power to about 12%  $P_0$  (i.e. to  $\Delta P_\infty \approx 3$  atm).

However, at large ratios  $\alpha_3/\alpha_2$  transients quality becomes slightly worse, their oscillations being increased. Indeed, increasing  $|\alpha_3|$   $X$  is decreased, and  $\gamma$  being increased, this is equivalent to the oscillation frequency increase and to the decrease in oscillation damping degree.

The theoretical results of dynamic properties investigations according to the methods described were verified in the course of preliminary experimental studies at the APEYC plant start-up and test operations (3). Experimental and design curves of power and pressure variations with 24% external electric load removing are compared in Fig.4.

Due to correction for pressure change in the setting of an automatic power regulator stable operation of the APEYC plant can be provided at full external load removing and increase. Then, steam pressure deviation from the nominal value will not exceed 2.5 atm.

Table I

Nomenclature

$\tau_0$	- time scale
$\lambda$	- radioactive decay constant of the delayed neutron emitter
$\rho$	- reactivity
$\rho_{rod}$	- control rods reactivity
$\alpha_T$	- coolant reactivity temperature coefficient
$\beta_T$	- fuel reactivity temperature coefficient
$C$	- specific heat
$M$	- mass
$KF$	- total heat flow per unit of temperature drop
$G$	- primary circuit coolant flow rate
$W_{turb}$	- turbine steam flow rate
$N_0$	- nominal reactor power
$\bar{\theta}_0$	- nominal average reactor coolant temperature
$\gamma' \gamma''$	- saturation water and steam densities, respectively
$r$	- steam generation specific heat
$i'$	- saturation water enthalpy
$i_{sw}$	- reactor input water enthalpy
$V_{steam}$	- secondary circuit steam volume
$V_{water}$	- secondary circuit boiling water volume
$T_{satur}$	- saturation water temperature
$\alpha_i$	- automatic control system coefficients
$\tau_1, \tau_2$	- transfer time delay in pipings from the reactor to the steam generator and in the opposite direction, respectively
$n$	- relative reactor power change
$C$	- delayed neutron emitters relative concentration change
$\vartheta_{in}, \vartheta_{out}$	- primary circuit coolant relative temperature change at the reactor inlet and outlet, respectively
$\vartheta_1, \vartheta_2$	- primary circuit coolant relative temperature change at the steam generator inlet and outlet, respectively
$u$	- fuel elements relative average temperature change
$P$	- secondary circuit steam relative pressure change.

Symbols

- $\rho$  - coefficient applied to the reactor  
 $sg$  - coefficient applied to the steam generator  
 $o$  - it denotes that a given value corresponds to plant parameters initial values.

Table 2.

Plant dynamic parameters

$$\begin{aligned}
 T_i &= \frac{\bar{\tau}_o}{\bar{\tau}_i} & \bar{\tau}_m, \bar{\tau}_l &= \left[ \frac{CM}{KF} \right] \\
 & & \bar{\tau}_n, \bar{\tau}_1, \bar{\tau}_2 &= \left[ \frac{M}{P} \right] \\
 & & \bar{\tau}_o &= \lambda^{-1} \\
 A_o &= \frac{N_o \bar{\tau}_o}{(CM)_m^p \bar{\theta}_o} & T^{sg} &= T^{sg} + 0.5 T_l^{sg} \\
 A_1 &= \frac{T_s^{sg} - 0.5 T_l^{sg}}{T^{sg}} & T_w &= \frac{W_{T_o} \bar{\tau}_o}{P_o \left( \frac{\partial \chi''}{\partial P} \right)_o V_{\text{steam}}} \\
 A_2 &= 1 - A_1 & T_{s_o} &= \frac{KF \bar{\theta}_o \bar{\tau}_o}{P \left( \frac{\partial \chi''}{\partial P} \right) V_{\text{steam}}} \\
 A_3 &= \frac{i' - i_{sw}}{r} \frac{T_w}{\left( 1 + \alpha \frac{V_{\text{steam}}}{V_{\text{water}}} \right)} & D &= \Psi A_v \\
 & & \Psi &= \left( \frac{\partial T_s}{\partial P} \right)_o \frac{P_o}{\bar{\theta}_o} \\
 A_4 &= \frac{0.5 T_{s_o}}{1 + \alpha \frac{V_{\text{steam}}}{V_{\text{water}}}} \\
 A_5 &= \frac{T_w}{1 + \alpha \frac{V_{\text{steam}}}{V_{\text{water}}}} & \alpha &= \left( \frac{\partial i' \chi'}{\partial P} \right)_o / r \left( \frac{\partial \chi''}{\partial P} \right)_o \\
 \alpha_p &= \frac{A_o T_l^p}{T_m^p T_n^p} & f &= \frac{D A_2 T^{\text{eff}}}{T_1 T_2}
 \end{aligned}$$

Table 3. Reactor effective dynamic parameters

With the automatic control system	!	Self-regulation
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$$K_i = T_m^P T_{ii}^P \left\{ 1 - \alpha_2 \frac{T_{ii}^P - 0.5 T_I^P}{T_m^P T_{ii}^P} - \alpha_5 \Delta p \right\}$$

$$K_i = T_m^P T_{ii}^P \left\{ 1 + \alpha_i \Delta p \right\}$$

$$K_e = T_m^P T_{ii}^P \left\{ 1 - \alpha_2 \frac{T_m^P + 0.5 T_I^P + T_{ii}^P}{T_m^P T_{ii}^P} - \alpha_5 \Delta p \right\}$$

$$K_e = T_m^P T_{ii}^P \left\{ 1 - (\alpha_e + \beta_0 T_0) \Delta p \right\}$$

$$T_i = - \frac{\alpha_2 + \alpha_4 \Delta p}{1 - \alpha_2 \frac{T_{ii}^P - 0.5 T_I^P}{T_m^P T_{ii}^P} - \alpha_5 \Delta p}$$

$$T_i = \frac{\alpha_i \Delta p T_0}{1 + \alpha_i \Delta p}$$

$$T_e = \frac{\alpha_2 + \alpha_4 \Delta p}{1 - \alpha_2 \frac{T_m^P + T_{ii}^P + 0.5 T_I^P}{T_m^P T_{ii}^P} - \alpha_5 \Delta p}$$

$$T_e = - \frac{\alpha_e \Delta p T_0}{1 - \alpha_e \Delta p}$$

### References

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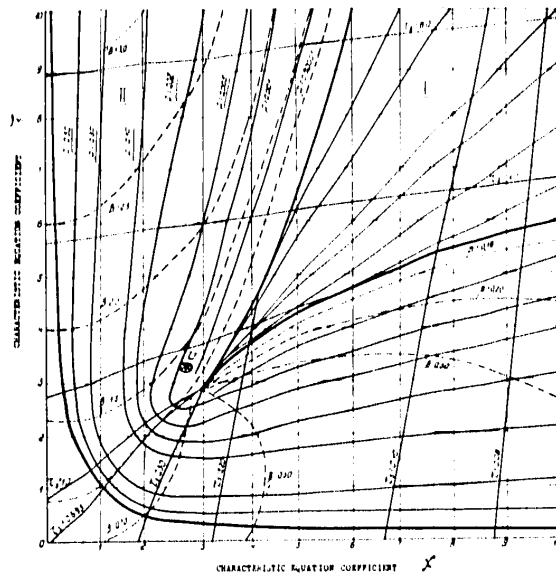


Fig. 1. Transient parameters diagram in the third order dynamic systems.  
 I - aperiodic stability region  
 II - oscillatory stability region  
 The point U corresponds to the APBYC plant parameters.

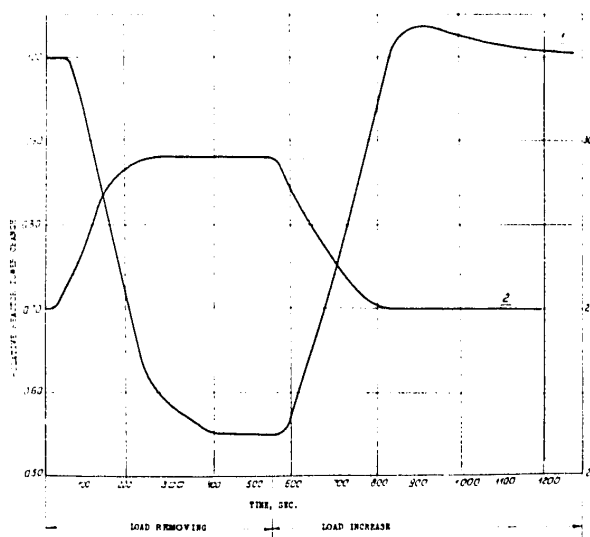


Fig. 2. Reactor power and steam pressure changes at load removing and subsequent 45% increase of it.  
 1 - Relative reactor power. 2 - Steam pressure.

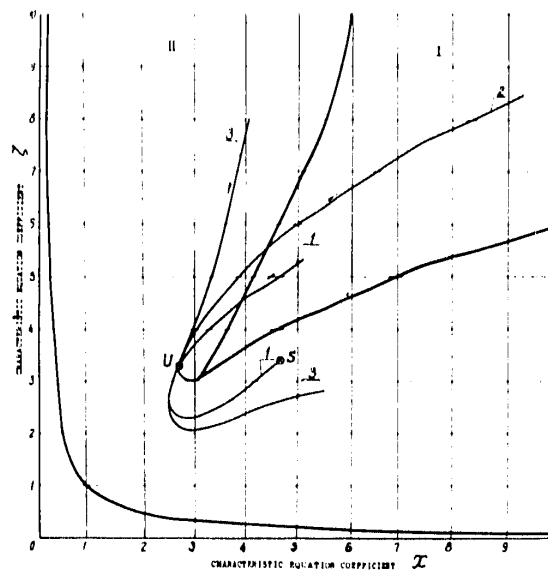


Fig. 3. Determining point path versus the parameters change of the APBYC plant at the self-regulation mode of operation. The arrows direction on curves corresponds to parameters increase:

- Curve (1)  $\alpha_r$  from  $-\infty$  to  $+0.001$   
 -- (2)  $\tau_{eff}$  from  $0.5 \cdot 10^{-2}$  to  $0.5$   
 -- (3)  $D$  from  $0.5 \cdot 10^{-3}$  to  $0.10$

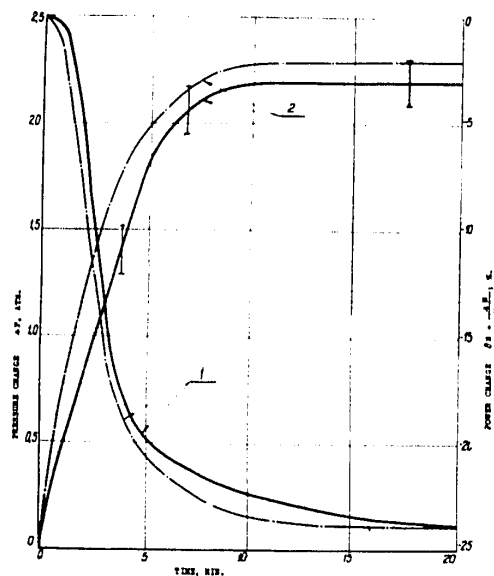


Fig. 4. Power and pressure change at load removing

- — — — — designed curve  
 — — — — — experimental curve  
 1. Power, %. 2. Pressure, atm.